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Modeling uncertainty creep due to variability in model constituents

David J. Parzych[a]
Power Acoustics, Inc.
12472 Lake Underhill Road #302
Orlando, FL 32828
USA

Robert A. Putnam[b]
Siemens Power Generation, Inc.
4400 Alafaya Trail MC Q2-286
Orlando, FL 32826
USA

ABSTRACT

Increasing cost consciousness in industrial plant designs is pushing industry toward ever decreasing acoustical design margins and associated costs, whenever possible. If industrial plant designers fail to properly account for acoustical design margins, the consequences can be serious. On one hand, reducing or removing design margins without fully understanding the consequences can result in facilities that do not meet the acoustical requirements. On the other hand, costs associated with over designed noise control could render a project economically infeasible. Understanding how the various aspects of uncertainty interact is imperative in minimizing both costs and risk in plant acoustical design. This paper addresses acoustical design uncertainty through the use of a Monte Carlo simulation analysis of the sound emissions from an example simple cycle gas turbine power plant. The results of this analysis reveal a significant and surprising aspect related to an uncertainty "creep" effect which the authors believe has not been considered in previous uncertainty analyses.

1 INTRODUCTION

The uncertainty associated with an acoustical design and sound measurements is based on many factors. Each of the uncertainty factors enters into a different phase of the design process and field verification of compliance. Each of the factors can add to the overall uncertainty of achieving critical design criteria. The acoustical design uncertainty can be broken down into three (3) categories:

1. The variability of radiated sound energy observed between two or more seemingly identical pieces of plant equipment. Although two components may be manufactured to the same drawings, manufacturing tolerances or changes in manufacturing processes can result in sound level differences between them. This is referred to in this paper as component to component variation.

2. The accuracy of the acoustical prediction methods, such as those based on the ISO 9613-2 standard. As with all prediction methods, the ISO 9613-2 based models use many approximations [1,2,3,4,5] to model source to receiver sound propagation.

3. The variability of measured sound level due to the equipment's placement or location, variations in site topography, minor changes in operating conditions, ambient conditions, instrumentation tolerances and personnel/procedures used to perform measurements. These items are "lumped" together as measurement uncertainty.

[a] Email address: info@poweracoustics.com
[b] Email address: bob.putnam@siemens.com

The interaction of the uncertainties defined above make defining the total sound prediction/measurement uncertainty a daunting task. The total uncertainty is based on a combination of the estimated uncertainty associated with each of the three major topics defined above. The uncertainty is defined in terms of standard deviations for each of the above issues by analysis of field test data and published values in American and International standards for noise measurement and noise prediction uncertainty.

The purpose of this paper is to evaluate the total system uncertainty by performing a Monte Carlo computer simulation of the uncertainties inherent in a typical simple cycle gas turbine power plant design.

2 DISCUSSION OF UNCERTAINTY TYPES

2.1 Determining Sound Level Differences Between "Identical" Pieces of Equipment

The range of sound levels observed between two or more pieces of the same equipment is difficult to define without obtaining a large statistical data base for each of the components of interest. Although two components may be manufactured to the same drawings, manufacturing tolerances or changes in manufacturing processes can result in sound level differences between them. Components manufactured with very tight tolerances and with consistent manufacturing processes are suspected to have much more repeatable sound level signatures than products designed for consumer household use. The above philosophy suggests that the repeatability of gas turbine equipment sound signatures should be relatively consistent. Variations in sound level, however, are commonly seen among seemingly "identical" pieces of equipment when measured in a laboratory situation by the same people, using the same measurement equipment. This variability in sound level is likely due to the small amount of energy consumed by the machinery to generate airborne sound relative to the amount of energy used to perform its function. As an example, the total acoustical power generated by a gas turbine is less than 1/100 of one percent (.0001) of the total electrical power generated. When a thermal performance difference equal to the total magnitude of the noise energy is observed there is no commercial concern. However, the energy associated with a difference in output power will likely be transferred into other forms of energy, such as heat or noise. Even when manufacturing variations between units cause small differences in performance (less than 0.05 percent), the difference in sound level can be several decibels if all the energy is converted into sound.

To determine the sound differences between seemingly identical pieces of equipment, data was selected from a data base of simple cycle gas turbine equipment. The data was analyzed to determine the mean sound power levels and the standard deviation associated with each piece of equipment. As much as possible, the uncertainty associated with measurement procedures, equipment and personnel have been minimized. It is assumed that the uncertainty associated with measurement accuracy has been reduced to negligible levels. The standard deviations provided in Table 1 are thus assumed to be representative of the true component to component variation.

Table 1: Example of combustion turbine and component sound power level variations (in standard deviations).

Type of Equipment	One standard deviation (σ) in dB(A)
Exhaust Stack Exit	2.4
Exhaust Stack Walls	1.8
Inlet Filter Face	1.3
Inlet Duct Walls	1.5
Generator	1.3
Turbine Enclosure	0.9
Lube Oil Coolers	0.8
Mechanical Equipment	0.9
Exhaust Expansion Joint	4.4
Transformers	3.8

2.2 Accuracy of the Acoustic Prediction Models

The second aspect of uncertainty is the accuracy of the available noise prediction models used for community noise modeling. Models based on various standards, such as ISO 9613-2[1], "enable noise levels in the community to be predicted from sources of known sound emission." As with all prediction methods, the ISO 9613-2 standard uses many approximations to model the sound propagation effects

The stated accuracy of a prediction method based on ISO 9613-2 is ±3 dB for distances less than 1000 meters from the source to observer at observer heights of less than 5 meters above the ground in "situations where there are no effects due to reflection or attenuation due to screening." It is assumed that the stated accuracy implies that the calculations will fall within this range.

2.3 Measurement Uncertainty and Instrumentation Tolerance

The broad range of effects that are lumped under the heading of "field measurement uncertainty" certainly makes sorting out systematic errors difficult. In most instances, the available data combines many uncertainties. However, it may not be necessary to define where the uncertainty comes from as much as whether or not it exists. Several American and International standards have made efforts to define such sound level measurement uncertainty errors[6,7,8].

When sound level differences are observed for a single piece of equipment that has been moved from one location to another, such differences can be explained as the result of changes in the environment or topography, variations in ambient conditions, small variations in the ability to repeat the operating condition or variability in the instrumentation, procedures or personnel used to measure the sound. For example, differences in sound level would be measured if a power plant was assembled at one site, then dismantled and reassembled at another site. Although all of the components would be the same and their sound signatures presumably constant, differences would be observed when the sound level was measured at the new site. Each of the field measurement uncertainty effects are known to cause variations in sound level.

Shown in Table 2 are the uncertainties associated with using some of the referenced International standard noise measurement procedures. Some sound level measurement standard methods were developed for laboratory environments while others are developed for field applications. Of particular interest are the standards often used for the measurement of sound pressure levels of gas turbine installations.

Table 2: Measurement uncertainty, expressed in standard deviation, provided by several different standards.

Standard	dB(A)	Measurement Grade
ANSI B133.8 [6]	3.0(*)	Survey
ISO 10494 [7]	2.0 or 5.0	Engineering or Survey
ISO 3746 [8]	3.0 to 4.0	Survey

(*) Based on similarity with the now withdrawn ISO 6190 standard.

The values provided include the cumulative effects of all causes of measurement uncertainty excluding variations due to local topography. Because these methods are only provided as a means of measuring the sound level of a particular installation, the variation between seemingly identical components is not included in the above standard deviations. Based on experience, however, many acoustical consultants and engineers believe that the uncertainty associated with measuring sound is typically less than those published by the standards.

2.4 Definition of "Uncertainty Creep"

Sound levels do not add linearly. If two identical pieces of equipment exist but one piece of equipment is incrementally noisier than the average of the two and the other is similarly quieter than the average of the two, the summation of two sources will tend to be higher than the summation of the two average sound levels, in decibels. This incremental, and always upward, shift is inherent in the logarithmic summation process and is what the authors describe as "uncertainty creep".

An example of uncertainty creep in a two component system is shown in the Table 3. Each of the components, on average, are expected to generate A-weighted sound levels of 50 dB(A) at a fixed distance. The sum of the two 50 dB(A) sources would then be 53 dB(A). Consider one possible case in which one of the two components is, in fact, 3 dB(A) higher than the expected average while the other happens to be 3 dB(A) lower (53 dB(A) and 47 dB(A)). The sum of the two components is 54 dB(A) or 1 dB(A) higher than the sound level made by the two "average pieces" of equipment.

Table 3: Sound level addition when 2 pieces of equipment are within one standard deviation of the average

Equipment	**Expected Sound Level**	**Standard Deviation (σ)**	**Actual Sound Level ± 1σ**
Component 1	50 dB(A)	3 dB(A)	53 dB(A) (average + 1σ)
Component 2	50 dB(A)	3 dB(A)	47 dB(A) (average - 1σ)
Sum	53 dB(A)	/////	54 dB(A)

In the situation where each of many components contribute differing levels of sound, as is the case with gas turbine power plants, the problem becomes more complex and requires a more refined analysis.

3 ANALYSIS - COMBINING THE UNCERTAINTY EFFECTS

The interactions of all the uncertainties previously discussed make defining the total sound prediction/measurement uncertainty a complicated task. The total uncertainty is based on a combination of the estimated uncertainty associated with each of the three major topics defined above. The uncertainty is defined in terms of standard deviations for each of the above issues by analysis of field test data and published values in American and International standards

3.1 Determination of Total Uncertainty with a Monte Carlo Simulation

The typical means of determining overall system uncertainty is through a root-sum-square analysis. However, because of the "uncertainty creep" demonstrated in Table 2, the authors believe the often used root-sum-squares analyses [9] does not adequately define the very complicated issues involved in estimating the overall prediction and measurement accuracy of a power plant application. To address the total system uncertainty, the authors performed a Monte Carlo computer simulation of the uncertainties inherent in a nominal 100+ MW simple cycle power plant. The simple cycle plant was selected because of a relatively large quantity of data that exists for the frame components. However, the uncertainties defined in this analysis are assumed to be representative of power plant equipment, in general, and are likely applicable to other frames or combined cycle applications.

Monte Carlo analyses typically are used as the basis for verifying mathematical approximations for statistical models. Monte Carlo simulations are known to provide the best statistical information for real life situations where mathematical models would be too complex or do not exist. The method is based on a computer simulation of an actual series of events that can take place, and then calculates the overall possibilities many times, each time introducing a new random path for each of the uncertainties. The most likely occurrence will happen more often, the least likely will happen less often.

Our Monte Carlo simulation is based on using a pseudo random number generator provided in a computer programming language package. We selected a normal distribution derived from each unique standard deviation for each equipment component or uncertainty in question. Stated in a very simplistic way, our model generates a random level of uncertainty for each of the sound sources based on its particular standard deviation (σ). The model then generates a random value of uncertainty for both the prediction method and the measurement uncertainty based on their own standard deviations. The component levels are summed logarithmically and the measurement uncertainty and prediction uncertainty are added linearly to the equipment levels. Each unique estimated sound level is then tracked in 1 dB(A) class intervals or bandwidths. For example, all values that are calculated between 59.5 and 60.5 dB(A) are placed in the 60 dB(A) band for accounting purposes. For the resulting analysis presented herein, the calculation procedure was repeated one million times until the distribution of sound levels no longer changed and the results were found to be stable and repeatable.

The Monte Carlo simulation does not provide a single number solution, but rather the probability of the expected outcome values. The simulation accounts only for the normally observed variation of equipment, measurements and prediction. The simulation does not account for incorrect specification of equipment by the acoustical engineer or for operating equipment in a manner other than as it was intended.

For each simulation of a “new plant”, the following assumptions were made:

- The major component sound power levels of a standard simple cycle gas turbine power plant acoustical design were used.
- Each major component in the plant was assigned a corresponding standard deviation for component to component differences, as defined in Table 1. Only those equipment components listed in Table 1 were considered for this analysis.
- The prediction model accuracy effects and the uncertainty associated with measurement precision are assumed to be unique and independent for each measurement position modeled. For the purposes of this analysis, the uncertainty of the prediction method was considered to be ±3 dB(A) and the uncertainty of the measurements was assumed to be ±1.5 dB(A).

Shown in Figure 1 are the plotted center points that resulted from an A-weighted sound level histogram generated with 1 dB class intervals or bandwidths. Three different combinations of component, prediction and measurement uncertainty are presented. Zero (0) dB(A) corresponds to the calculated sound level with all equipment generating “average sound levels”. It can be seen that the overall uncertainty becomes substantially greater (broader bell curves) when prediction and measurement uncertainty are included. Of particular interest is the shifting of the bell curves such that they are slightly offset, toward higher sound levels, from the “average” sound levels or those that would be calculated using average equipment sound power levels with a computer method utilizing ISO 9613-2 calculation methods. This offset is the uncertainty creep effect.

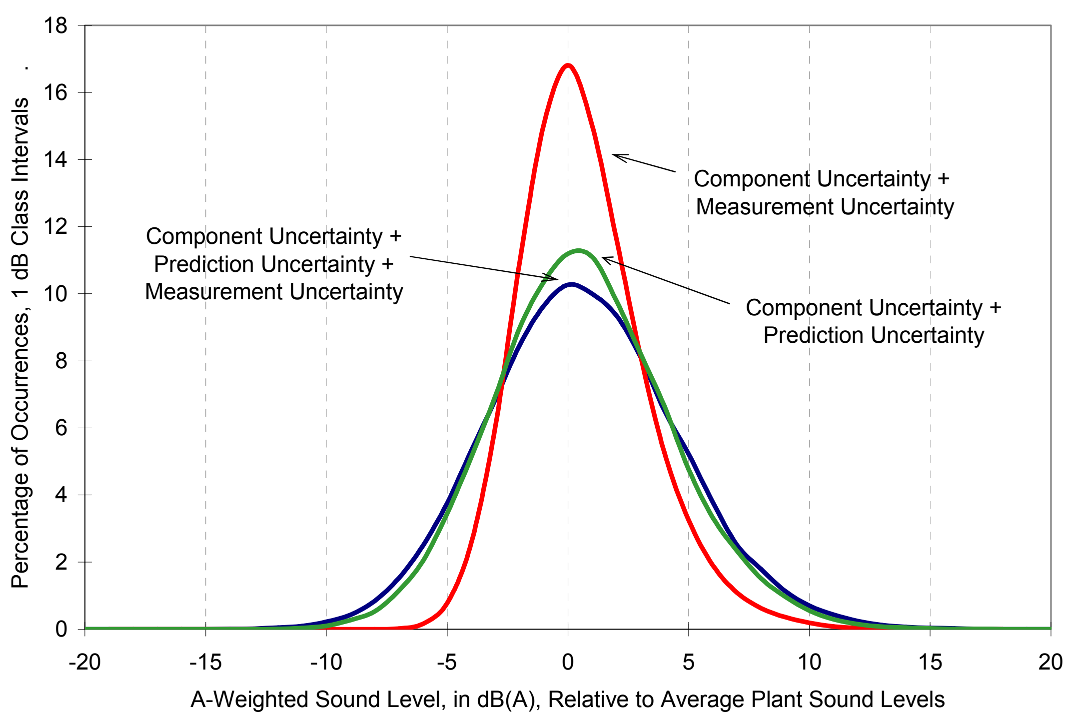

Figure 1: Estimated A-weighted sound level distribution for a simple cycle combustion turbine based power plant

Figure 2 depicts the cumulative distribution of the A-weighted sound levels discussed in the previous figure, showing more clearly the offset referred to as the uncertainty creep effect. Of particular interest is that the cumulative distribution curve does not cross the 50% value at zero dB(A) but at a point in the vicinity of +1 dB(A). The "creep effect", in this case, will diminish any design margins by about 1 dB(A) otherwise incorporated into the plant design. Therefore, an "average plant" is estimated to exceed the average estimated design sound level criterion about 60% of the time due to the offset caused by the upward uncertainty creep. Likewise, Figure 2 tells us that to achieve sound level objectives 70% of the time, a 3 dB(A) margin would be required. For a 98% or greater probability of achieving sound level criteria, a margin of 10 dB(A) is estimated as necessary.

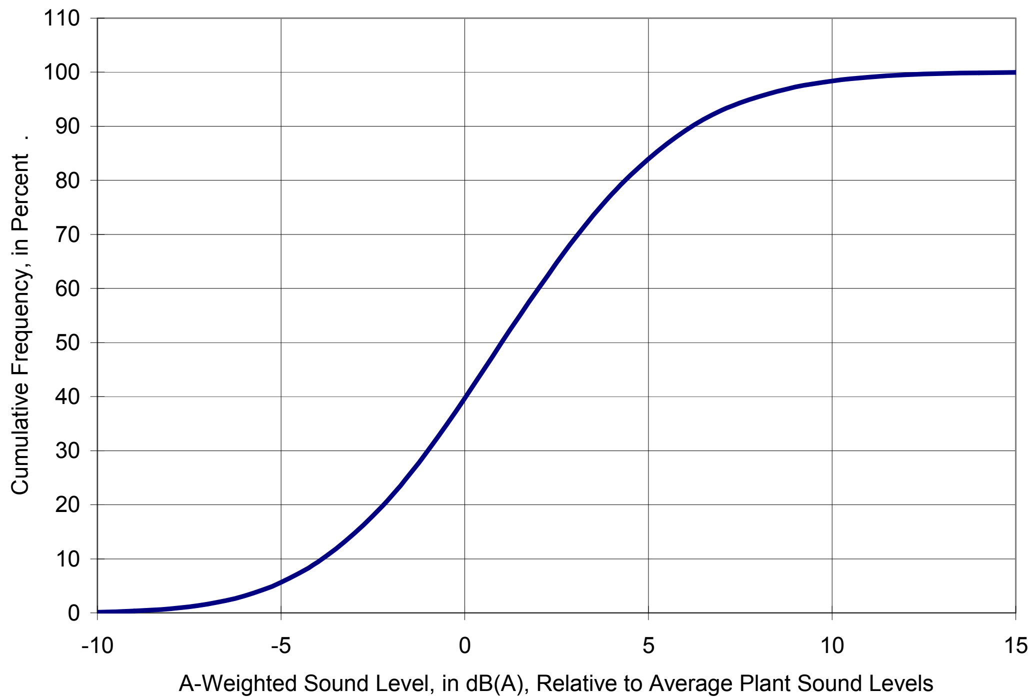

Figure 2: Cumulative frequency distribution of a typical simple cycle combustion turbine based power plant with component, prediction and measurement uncertainty

4 SUMMARY

An analysis utilizing a Monte Carlo simulation to evaluate sound level design uncertainty has revealed a significant and surprising aspect related to an "uncertainty creep" effect. The uncertainty creep originates with the nature of the logarithmic summation of decibels which the authors believe has not been considered in previous sound level uncertainty analyses. For large industrial equipment installations, such as those used in a simple cycle gas turbine power plant, it was found that the uncertainty creep effect can cause significantly more than half of plant designs to exceed the design sound level criterion when a database of "average equipment" component sound levels is used for design purposes. The analysis in the example case evaluated has indicated that a 3 dB(A) design margin will result in a confidence level of approximately 70% while a design margin of approximately 10 dB(A) is necessary for a 98% confidence level.

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Power Acoustics, Inc.

The proceeding paper was authored by **Dave Parzych, Principal Acoustical Consultant and Noise Control Consultant of Power Acoustics, Inc.**

For more information on how Power Acoustics, Inc. can help you, contact us at:

12472 Lake Underhill Rd, #302 • Orlando, Florida • 32828
Phone: (407) 381-1439 • Fax: (407) 381-6080
Email: info@poweracoustics.com

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